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Design, development and technological advancement in the biomass cookstoves: A review

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ABSTRACT

The use of biomass resources for cooking and heating is as old as the origin of human civilization due to the fact that biomass is available almost everywhere and can be burnt directly. Biomass accounts for a large fraction of the domestic energy needs in the developing countries. However, very often biomass is burnt inefficiently in open three-stone fire and traditional cookstoves for cooking and heating applications which causes severe health problems in women and children and also affects the environment. Many efforts have been made worldwide to increase the dissemination of improved cookstove but have not succeeded in their targets. The new cookstove dissemination programs can be funded through carbon revenue and other funding organizations; further these funds can be utilized for further R&D and cookstove market. The successful cookstove dissemination programs can lead to the sustainable development of the rural areas besides helping in the commercialization of cookstove. Therefore, this article presents the review on the design, development, and technological advancement of biomass cookstoves and the effects of traditional biomass burning devices on the emission, health hazard, and environmental pollution.

Contents

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1. Introduction

It is estimated from the historical evidences that fire has been used for cooking of meals for about 100,000 years [1]. However, during the earlier ages, the cooking was done over an open-fire for roasting of meat and to protect from the wild animals. The modification in the pots of various shapes and sizes led down in the development of the open-fire to shielded-fires. The simplest and most common form of the shielded-fire was the three-stone fire arrangement and later on with the developments, it had changed to a U-shape mud cookstove called traditional cookstove [2]. Early development of biomass based cookstoves started in India during the 1940s [3]. More extensive research and development activities on the improved cookstoves took place all over the world after the 1970s oil crisis due to which many improved cookstove programs (ICPs) were initiated in a number of developing countries including India to tackle the energy crisis, deforestation, smoke reduction in the kitchen and so on. Although these programs started in different countries implemented by various different government agencies, NGOs, donor organizations etc., they could not achieve the required objectives due to various reasons and constraints [4]. During the 1980s and 1990s, the research work mainly was devoted to household energy issues in the developing countries because at that time, the problem was viewed mainly as an inter-fuel substitution or biomass energy-efficiency issue, which was about fuel scarcity and deforestation [5].

In the beginning of the 1990s, more focus was shifted toward the research on issues involving the indoor air pollution (IAP) and its effects on health [6]. As stated by Smith et al. [7], the burning of biomass fuels emits very high levels of smoke containing hazardous pollutants that include respirable particulate matters (SPM), carbon monoxide (CO), nitrogen oxides (No_x), sulfur oxides (SO_x), and a host of organic compounds, some of which (e.g. benzo(a) pyrene, benzene and 1,3-butadine) are commonly known as human carcinogens. Fullerton et al. [8] presented the health impacts and associated risks of the indoor air pollution due to biomass fuel use. They stated that different types of health risks were associated with the indoor air pollution, such as respiratory infections including pneumonia, tuberculosis, and chronic obstructive pulmonary disease, low birth weight, cataracts, cardiovascular events and all-cause mortality in household members. Kleeman et al. [9] studied the adverse health impacts of the particle size distribution and result of deposition of that pollution in different areas of lungs. Venkataraman et al. [10] stated that the biomass fuels had a heavy burden of time and money on the world's poorest groups. The world health organization (WHO) has estimated that every year around 1.5 million people died and many others became victims of different diseases due to smoke from open fires and traditional cookstoves [11]. Ramanathan and Carmichael [12] recently studied that the black carbon is playing a major role in the global warming.

To curb all these effects mentioned above, numbers of efforts have been made worldwide. Zhang et al., [13–15] reported a comprehensive database for CO emission ratios and CO emission factors for both per-fuel mass basis and per-cooking-task basis, respectively. Further, the estimation of CO concentrations and exposures were also presented a hypothetical village kitchen resulting by using a range of fuels with different cookstoves, commonly used in the developing countries. The emission factors for different combinations of fuels and stoves were tested in China for direct and indirect green house gases (GHGs) as well as other airborne pollutants, such as, carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), total non-methane hydrocarbons (TNMHC), nitrous oxide (N_2O), sulfur dioxide (SO_2), nitrogen oxides (NO_x), total suspended particle (TSP) etc. for a typical set of operating parameters [15]. The Global Alliance for Clean Cookstoves (GACC), a new public–private partnership led by the UN Foundation, took initiatives to create a thriving global market for clean and efficient household cooking solutions [16]. The newly designed cookstoves which are known as advanced biomass cookstoves are based on better design principles, as they have the better combustion efficiency and thus, reduce the fuel consumption to a greater extent. These cookstoves can then deal with both the emissions and health issues, resulting from cooking with open fires or traditional biomass cookstoves. These cookstoves have the ability to get carbon credits [17] not only because of their contribution to climate-change mitigation but also they can yield major co-benefits in terms of energy access for the poor people, besides they may result in improved rural health, environmental, agricultural and economic benefits [6].

2. History of cookstove

The history of cookstove had started with the invention of fire and from archeological excavations at Chou Kutien in China. It had been shown that the Homo erectus pekingnensis used the fire for heating during the first ice age of about 400,000 years ago [18]. However, the human civilization had started by making the use of refined stones, the mastery of fire, and the domestication of several animals and cultivation of plants [1]. During the earlier age cooking especially, the roasting of meat was done mostly over an open-fire and the fuel used to be arranged in a pyramid configuration for cooking. The development of open fire to improved cookstove took place with time as the human civilization progressed and some of the facts are given as below:

2.1. Open fire to traditional cookstoves

Initially, the development of pots was a major step toward the development of other types of cookstoves. Later on, the open-fire transformed into shielded-fires to balance the pot over the fire. The initial and simplest form of the shielded-fire was a three-stone arrangement. In this arrangement, the stones were arranged at suitable angles on the plain ground to support the pots of various sizes, which improved the cooking efficiency and reduced the scattering of fire from windy conditions. With the developments of the shielded-fire, the three-stone fire gradually changed into a U-shaped mud enclosure. Also, for induction of secondary air required for better combustion of volatile matter and for the exit

of flue gas, three small humps were put at the top of the stove. Additional holes connected with tunnel for pots were later added to conserve heat from the hot flue gases and to enhance the cooking efficiency and productivity. However, earlier innovations had increased the cooking efficiency of various systems up to an extent but the health and environmental hazards could not be considered due to lack of awareness at that time [2]. All the cookstoves developed during early time (i.e. before 17th century) were called as 'traditional cookstoves' because their thermal efficiencies were very low and the material of construction was also very poor besides, they emitted a very high level of smoke.

The developments in the biomass-based cookstoves started in India in the early 1940s. These cookstoves were called as improved mud cookstoves or first-generation flued (FGF) cookstoves. The first improved mud cookstove named, 'Magan Chulha' [3], was developed during 1947 in India. The improved multi-pot mud cookstoves were introduced by Raju [19] for rural households in India. Theodorovic [20] conducted the laboratory tests on biomass burning improved cookstoves in Egypt in 1954. Singer [21] measured the efficiency of improved multi-pot cookstove in Indonesia during 1961, which was originally developed by Raju [19]. In these improved cookstoves, a chimney was provided to remove smoke from the kitchen; however, they were madeup of high-mass and had adjustable metal dampers to regulate the air–fuel control system.

The next wave of improved cookstoves appeared during the 1970s, when global attention was turned toward environmental issues and energy conservation measures. A number of models of improved wood-burning cookstoves (ICS) known as second generation flued cookstoves (SGF), were developed. These cookstoves were designed and fabricated based on the engineering principles and hence, were more efficient and durable as compared to those of the first generation cookstove models, mentioned earlier. The aim of the design was to increase the efficiency with the idea to decrease the fuel consumption in order to prevent not only the deforestation but also to lessen the drudgery and/or expense of procuring the cooking fuel with the emphasized on smoke reduction. Finally, the second generation unflued (SGU) cookstoves were developed to raise the fuel utilization through improved combustion and heat transfer efficiency. It was considered that due to the improved combustion, the emissions per dish would be less and hence, emission level will come down [22]. The higher thermal efficiency was achieved with the use of baffles, dampers and smoke reduction in kitchen premises with the help of a chimney. However, in most of the cases, the dampers were not used by women resulted in consumption of more fuel due to free access of air into the fire box. The main reason behind it was that the dampers were metallic, caused burn injuries and hence, it was difficult for women to use it properly during cooking. Keeping in mind these difficulties faced by the rural women, cookstoves without damper were also developed [23].

2.2. Improved cookstove programs

Since, poor people could not afford or obtain modern stoves and fuels. Therefore, it was emphasized to develop more efficient, energy-saving, and inexpensive biomass cookstoves, which could help to alleviate pressure on wood resources, to shorten the walking time required collecting the fuel, to reduce the cash outlays necessary for purchasing the fuel wood or charcoal, and to diminish the pollution released into the open environment. The potential benefits of the modern and efficient biomass cookstoves had been obvious, since, the first discussions of the "fuel-wood crisis" and many programs were undertaken to make improved biomass cookstoves available to the potential users and they were disseminated widely around the world. The attempts were made from time to time to assess very diverse and mixed success of the hundreds of cookstove programs that had been implemented worldwide [24].

In the recent decades, various agencies including NGOs had been working toward the dissemination of the improved biomass cookstoves, although the improved cookstoves could not be disseminated more in numbers as compared to the numbers of households targeted in these programs. The major difficulty that encountered in the cookstove dissemination was not adopting the improved cookstove by the rural households. This is due to the fact that people in rural areas used locally available material especially, clay and argo-residue to fabricate and repair their traditional cookstoves and hence, no expenditure occurred on fuel and cookstove maintenance. Therefore, NGOs and other agencies involved in dissemination programs had to establish reliable systems for the production, distribution, installation and maintenance of improved cookstoves. Kenya's Maendeleo cookstove program was the only one that had established itself as the self-sustaining system. The future prospects of the dissemination programs could be better by increasing awareness of the health benefits of improved cookstoves [25]. Tukana and Lloyd [26] studied the cooking habits and woodstove cooking experiences of typical rural villages of Fiji. They concluded that the current cookstoves were more efficient than the open fire, and hence, they emphasized on providing more accessible fuel to the households and the kitchen environment.

Smith et al. [27] examined the 'Chinese National Improved Stove' program that introduced approximately 129 million improved biomass cookstoves into rural areas during 1982–1992. China's National Improved Stove program was a successful program for improved cookstoves because more than 100 million improved cookstoves are still in use. The program was focused on energy efficiency and removal of smoke from the household with the help of chimney based cookstoves. Although this program was no longer funded, but the private sector has produced stove components that lead the way to the development of more efficient and less polluting cookstove models [6].

In India, the Ministry for New and Renewable Energy (MNRE), earlier known as Department of Non-conventional Energy Sources (DNES) launched a National Program on Improved Chulhas (NPIC) in 1985–1986. The program was started with few good objectives including (i) reduction of deforestation and smoke through fuel wood conservation; (ii) reduction in the drudgery tasks to be performed by women and children; (iii) health hazards due to exposure to smoke; and (iv) the employment in the rural areas. More than 60 fixed and portable type of models with or without chimney, single-pot or multi-pot, suitable for different fuels, cooking habits and local requirements, using different materials of construction were developed and installed under this program. Since, the end-user wanted more versatility in the fuel usage and less time in cooking, while, the improved mud cookstoves were designed by the institutions on the objective of fuel economy and less smoke. Whereas, the rural people were not concerned much about the cooking fuels and deforestation at that time, as a result, the success was much below the expectation level with which it was started. Apart from the traditional cooking practices, the non-replacement of traditional cookstoves with the improved cookstoves was also influenced by socio-cultural factors and other benefits such as, space heating by traditional cookstoves. From the above experiences, it was learnt that the success of an improved cookstove program depends on the assessment, surveys, proper monitoring, evaluation and cultural barriers [4]. A total of 33.8 million improved chulhas had been installed with varying degrees of success and finally, this program was formally declared closed in the year 2004 [28].

However, findings from different dissemination projects exhibited that a strong political influence, effective policy and mass movement is required to facilitate the development of the next generation biomass cookstoves for household and community cooking to get the benefits of health, mitigation of climate change and energy conservation [29]. In this regard, the United Nations has fixed the target known as UN Millennium Project and the objective of the project is to halve the number of people without access to modern cooking fuels by 2015. Thus, the use of energy efficient and clean-burning cookstoves is one of the means that can help to achieve the objective of this UN Millennium Project. The commitment of donors and therefore, the public sector will play a critical role. The dissemination of cookstoves requires public sector investment, which may be International and/or National. The public finances should be used for capacity development through awareness programs for further technological development and finding the appropriate dissemination strategies. Besides, a supportive political frame-work is required for disseminating the biomass cookstove for a sustainable development worldwide.

Apart from the dissemination and design strategies mentioned above, a greater RD&D has been undertaken through detailed studies on thermodynamic, heat transfer and aerodynamic to develop a more efficient, affordable and durable biomass cookstove. The design principles along with the systematic testing and design procedures for cookstoves were also implemented worldwide after 1970s [2]. Micuta in 1985 investigated the design principles, procedure and idea of placing a short chimney above fire to reduce the harmful emissions [30]. Winiarski [31] developed various design principles to improve combustion and heat transfer efficiency and developed famous 'Rocket stove' in 1980. Many cookstoves have been developed based on their design principles. Some of them are HELPS plancha stoves in Guatemala, PROLENA EcoStoves in Nicaragua, GTZ cooking stoves in Africa, Justa stoves in Honduras, etc. [32]. At a later stage Baldwin [33] also carried out a detailed study on the improved cookstove design using different design principles and evolved the concept of pot skirt. Reed [34] in 1985 developed the concept of micro-gasification which could become the base for the development of gasifier and pyrolytic gasifier cookstoves.

The case of Uganda has proven that the large-scale introduction of cookstoves is possible. During the last decades, many developmental projects have been successfully introduced the improved cookstoves that burn biomass efficiently and thus, could reduce the emissions and consumption of natural resources. However, scaling-up still remains a major challenge. In the 1980s, the dissemination strategies mainly focused on self-help approaches or distribution of stoves for free. Experiences have shown that these approaches were not always supportive for the construction of high quality stoves, thus, evoking a negative image of stoves that break easily and it is not found to be worth to spend money on them. Due to weak or non-existing markets, public investment through national governments, international donor organizations or NGOs are needed in the beginning to support the setting up of a business oriented market. Raising the knowledge and awareness are the important factors to increase the demand for improved cookstoves, thus, production and marketing of cookstoves are required [29]. Bazilian et al. [35] described the emerging public–private partnerships in the field of modern fuels and improved cookstoves to provide the modern cooking fuel to the poor people in the developing countries for their social and economic developments.

As mentioned earlier, some improved cookstove programs were based on smoke reduction from kitchen premises only. While the experiences gained from different projects around the globe, exhibits that the improvement and modification are required in the cookstoves design and dissemination strategies. The awareness about adverse health impacts due to incomplete combustion of biomass had increased with a need to take effective steps to improve indoor air quality in the rural households by providing cleaner cooking options such as improved cookstoves. Due to the increasing concerns about the climate change and outdoor air quality, it is not sufficient to remove the smoke from the kitchen only using a chimney but also there is a need for providing biomass burning cookstoves with cleaner combustion, which emit low level of emissions and easily accessible to the common people at an affordable price.

There is a scope for further supporting the technical development of a wide array of cookstove types and facilitating their innovation to meet performance standard benchmarks. Apart from the technology, widely accepted standards and testing protocols are needed to qualify advanced biomass cookstoves as safe, durable, efficient, and clean burning. One could encourage the development of a wide variety of low-cost or inexpensive cookstoves that meet certain minimum standards and expand their marketability, as already initiated by the World Bank in Africa [35] and also proposed under India's new biomass cookstove initiative [36]. Since, much of this work will involve the private sector, the International Finance Corporation (IFC), with its ability to provide private companies loans and technical assistance directly, could play a significant role in strengthening the emerging cookstove companies and manufacturers, as well as supporting the process of performance-based cookstove certification. The goal would be to facilitate the adoption of better stoves through promotion of businesses for designing, producing, and marketing of improved and valued cookstoves. Some of the world's major manufacturers and an increasing number of foundations including NGOs have involved in the development of improved and advanced biomass cookstoves. These include the Shell Foundation, Phillips, Appropriate Rural Technology Institute (ARTI), Technology Informatics and Design Endeavors (TIDE) and others [28]. To finance both the advanced and improved cookstoves, three major funding sources viz. (i) Global environment facility grant funding (GEF); (ii) Carbon credits; and (iii) Climate Investment Funds could be used to support the cookstove dissemination projects in different countries [6].

3. Recent developments in cookstove

Due to scientific and technical advancement through RD&D in all sectors of Science & Technology during the recent decades, the design, modeling, and advancement of cookstove have taken place around the world. However, the cookstove could not be made available to the poor and needy people in both urban and rural sectors due to different constraints [6] even though the Government, NGOs and other organizations have made numerous efforts. During the recent years, few techniques, such as, design principle, mathematical modeling and material selection were studied by number of authors [30–34].

3.1. Technological advancements

To increase the combustion and heat transfer efficiencies of cookstove through different mechanisms, few components such as, grate, pot skirt, dampers, etc. were developed and introduced by number of authors [30–34]. Recently, the research on emissions reduction brought to a new stove technology, called gasifier and pyrolytic stoves which is based on the micro-gasification principle. The efficiency and emission reduction were achieved by generating and separating the combustible gases from the biomass through gasification and burnt these gases as the gaseous fuel

[34]. The development in cookstove with the passage of time is shown in Fig. 1.

3.1.1. Material of construction

The earlier improved cookstoves generally had the chimneys and closed combustion chambers. These improved cookstoves were roughly counted to 166 millions in number of households including 116 millions in China, more than 13 millions in the rest of East Asia, nearly 22 millions in South Asia, of about 7 millions in the Sub-Saharan Africa, and over 8 millions in the Latin America and the Caribbean. From 1980 until about 2002, thousands of artisans produced and disseminated the improved cookstove models. As one might imagine, such cookstoves easily cracked and degraded with repeated heating and cooling. Their estimated two-year life span proved to be too optimistic; in practice, whereas, some failed within a year [6].

The recently developed advanced biomass cookstove are based on the higher level of technical research, and are generally more expensive. These cookstoves consist of better technological and design features such as grates, insulation, forced air flow, and more durable materials to provide a cleaner burning and hence, more efficient devices. These cookstoves include the wood, charcoal, pellet, and gasifier cookstoves. The lower-cost improved cookstoves can also significantly lower the emissions, improve the health, and reduce the forest degradation and deforestation. Therefore, the systematic investigation of the heat transfer and combustion efficiency of a stove design is necessary in the laboratory, which in turn, may help to ensure that the cookstoves to be disseminated have a significant improvement over the traditional one. Thus, the new cookstoves should be based on the well-defined standards that include safety, efficiency, emissions, durability and cost.

3.1.2. Mode of air supply

The combustion efficiency should be improved to reduce the smoke and harmful emissions by improved heat transfer efficiency leading to a lesser fuel consumption. The newly developed batch feeding and forced draft concept may increase the overall efficiency of the cookstove [32]. If the air entered through free convection in a cookstove, is called a natural-draft stove and if

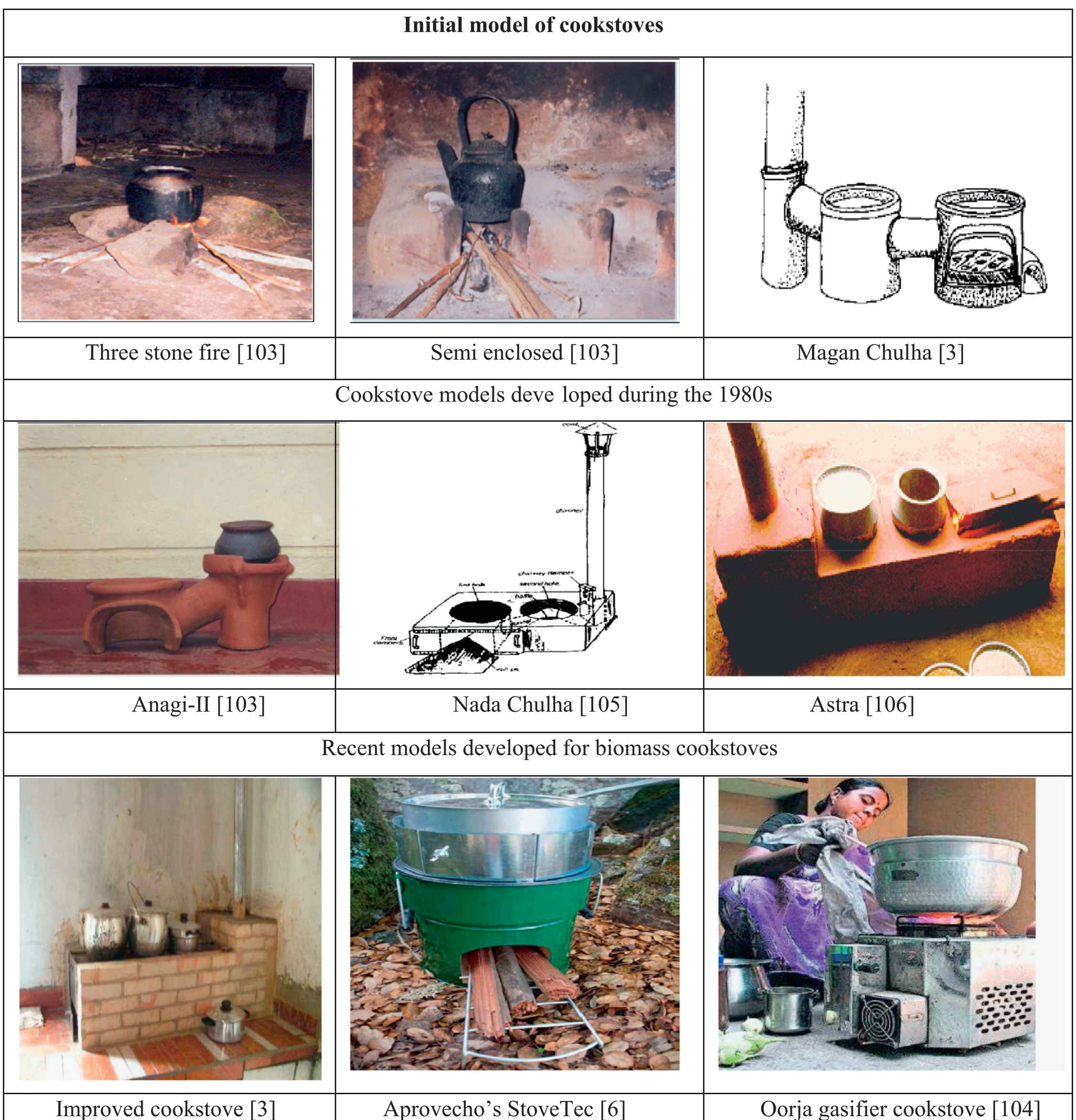


Fig. 1. Development of different cookstove models.

the air is supplied through a fan, it is called a forced draft stove. In a natural draft stove, the better mixing of combustible gases could not take place. Therefore, the stove developer has to improve the combustion efficiency with the help of better stove geometry and new materials. On the other hand, in a forced draft stove, the better mixing of combustible gases and oxygen leads to an improved combustion and hence, to lower emissions.

In a traditional mud stove, gasification and combustion of fuel take place almost simultaneously around the solid fuel, which leads to higher emissions due to incomplete combustion. During the pyrolysis of the solid biomass fuel, the volatile gases and char formed. After releasing the volatile gases, the char gasification initiates which lead to emission of carbon mono-oxide. The combustible gases i.e. mixture of volatile gases and carbon mono-oxide subsequently react with oxygen, present in the air entering into the cookstove due to the natural draft, induced by the chimney effect. In recent years, the natural and forced draft, and gasifier stoves were designed to improve the combustion efficiency. In a gasifier stove, the generation and separation of combustible gases from fuel and its subsequent combustion take place to produce heat, which leads to a higher combustion efficiency and therefore, reduces the emission of incomplete combustible products [37].

3.1.3. Testing protocols and standards

Since, the cookstove performance greatly varies from the lab to the field and it was felt that a cookstove should be tested according to some standard test procedures to get the realistic results. These test results can be used to improve the design and performance and may guide for implementation decisions. The different testing protocols and standards have been developed around the world for testing and designing the improved biomass cookstoves. Currently, there are three types of testing protocols, such as, water boiling test (WBT), controlled cooking test (CCT) and kitchen performance test (KPT) for wood–biomass cookstoves [39]. The first version of water boiling test (WBT) was prepared by VITA (Volunteers in Technical Assistance) in 1982. Later on the WBT was revised and added by two more field tests named as Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT) in 1985.

In 2003, the Aprovecho Research Centre along with University of California at Berkeley revised the VITA protocols with the important changes in WBT as well as CCT and KPT. This version of water boiling test was named as WBT 3.0. Since 2007, PCIA (Partnership for Clean Indoor Air) and the ETHOS (Engineers in Technical and Humanitarian Opportunities of Service) had been working toward further development of these protocols. The protocol also has the flexibility of being applied to the new type of the stoves, e.g. gasifier stoves or other stoves using prepared fuel. This protocol is designated as Stove Manufacturers Emissions and Performance Test Protocols.

In 1991, Bureau of Indian Standards (BIS) adopted the water boiling test as its own standard to test the biomass cookstoves, which also includes the measurement of CO/CO_2 ratio as a separate test [27,38]. The new version of WBT designated as WBT 4.1.2 is now available for the measurement of emissions of different pollutants along with the thermal efficiency of cookstove. There are several cookstove test protocols and standards available to measure the thermal efficiency and emissions all over the world. However, there is no specific test protocol and standard which is internationally approved for all cookstove models. The detail about each test is described as below:

3.1.3.1. Water Boiling Test (WBT). This is a laboratory test that is used to evaluate the stove performance, while, boiling and simmering the water in a controlled environment to investigate the thermal efficiency of the stove. This test provides the stove designer reliable information about the technical performance of wood burning stove models. The test consists of three phases that determine the stove's ability to (i) bring water to a boil from a cold start; (ii) bring water to a boil when the stove is hot; and (iii) maintain the water at simmering temperatures. The wood used for boiling and simmering, and the time to boil are determined. It takes into account the moisture content of the wood, steam generated and other factors in the water boiling test, which allows making the comparison among different cookstoves [32,40].

3.1.3.2. Controlled Cooking Test (CCT). This is a field test that is used to evaluate the stove performance of a new cookstove under the common or traditional cooking methods. CCT is designed to compare the different cookstove's performance in a controlled manner by controlling fuels, pots, and operation of the stove. Local users prepare a traditional food on the stoves, so that stoves can be compared, by cooking the same food in the same pot and give their opinions for modification in the cookstove model. It reveals what is possible in households under ideal conditions. The CCT stimulates the actual cooking, when the stove subjected to more realistic through controlled conditions. The test is performed for evaluating the following aspects regarding the cookstove; (i) to compare the amount of fuel used by different cookstoves to cook a food or meal, (ii) to compare the time needed to cook that food, (iii) to inquire the likeliness of users for the new stove to cook their favorite food, and (iv) to investigate the emissions made during the test of the old and new stove [40].

3.1.3.3. Kitchen Performance Test (KPT). It is also a field test that is used to evaluate the performance of a stove in the real-world conditions in the field. KPT is designed to determine the effects to introduce a new stove in a community and to evaluate the energy conservation impact of the new stove on the kitchen energy. Families are selected in a community who adopt the new stoves and field survey to be done for evaluation of the performance of the stoves. The following aspects regarding the fuel use in a community can be evaluated by this test: (i) to find out the difference in fuel used between households using traditional stoves and households using the new stove, (ii) to find out the medium or long term fuel used to determine, if changes are sustained in the long term, (iii) to test for seasonal changes in the fuel consumption, and (iv) to test for differences in the fuel used among households using the same cookstove but burning different type of fuels [40].

Recently, Envirofit and Philips have come together to modify the available protocols to suit the requirements of their designs. The International Standards Organization (ISO) Workshop held on cookstoves during 28–29 February, 2012 in The Hague, Netherlands, which was attended by more than 90 stakeholders. This workshop was organized jointly by the Partnership for Clean Indoor Air (PCIA) and the Global Alliance for Clean Cookstoves (GACC) with the support of the American National Standards Institute (ANSI). The objective of the workshop was to develop globally recognized standards for clean and efficient biomass cookstoves. In this workshop, an International Workshop Agreement (IWA) was finalized and confirmed by majority of stakeholders to provide guidelines for rating the cookstoves in terms of the performance indicators such as, efficiency/fuel consumption, emissions and safety [41].

Adkins et al. [42] conducted two different studies to evaluate the performance and usability of household biomass cookstoves under field conditions in rural sub-Saharan Africa. The CCT, KPT

and the qualitative surveys were performed and the results of improved cookstove models, such as, Stove Tech, Envirofit, Uga stove, Advent stove were compared with the traditional three-stone fire. In these studies, the specific fuel-wood consumption and the cooking time were the performance parameters, evaluated during these cooking tests. The test results showed that the manufactured stoves, in general, yielded a substantial reduction in the specific fuel-wood consumption relative to the three-stone fire and also these results varied with the stove type and the type of food cooked. Their data suggested that the overall stove preference depends upon a combination of fuel-wood savings and other factors, including cooking time, stove size and ease of use. They also suggested that these cooking tests with qualitative surveys can be used to determine the degree of suitability of a typically manufactured cookstove for an individual household.

Bailis et al. [43] described the monitoring and evaluation report of three improved cookstove dissemination projects implemented between 2004 and 2006 by different non-governmental organizations (NGOs) in India and Mexico. The stove performance using WBT, and performance parameters such as, time to boil water, specific fuel consumption and energy efficiency were assessed in these projects, when the stove was operated at both high- and low-power output. On the other hand, KPT and CCT were conducted to evaluate per capita fuel consumption on daily basis. In these tests, the improved cookstoves (ICSs) were compared with the local traditional cookstoves (TCSs). Although, the ICSs were found to be slightly better in efficiency for the low-power simmering phases, but they were found to be less efficient than those of the traditional stoves in high-power water-boiling phases. However, all the improved cookstoves showed the larger reductions (from 19% to 67%) in the average fuel consumption per capita.

MacCarty et al. [44] investigated the performance of 50 different cookstoves, including the simple stoves without combustion chambers, stoves with rocket-type combustion chambers, gasifier stoves, fan-assisted stoves, charcoal-burning stoves, liquid/gas fuel stoves, and wood-burning stoves with chimneys. They compared the fuel consumption, emission of carbon monoxide (CO) and the particulate matter (PM) of all cookstoves with the three-stone fire cookstove. From this comparative study, they concluded that the Rocket-type stove reduced the fuel consumption by 33%, CO emissions by 75% and PM emissions by 46% as compared to the three-stone fire cookstove. It was also observed that the use of a pot skirt reduced the fuel consumption and CO emissions by 25–30%, while, the gasifier stoves reduced the particulate matter on an average of 90%. On the other hand, the forced air stoves reduce the fuel consumption by 40% and emissions by 90%, while, the use of the traditional charcoal stove produces carbon monoxide more than two times and the particulate matter 80% less as compared to the three-stone fire stove, while consuming the same amount of energy. For a rocket-type charcoal stove, the reduction in the fuel consumption was found to be one third and the CO emission was found to be half as compared to the three-stone fire stove. They also mentioned that a well-designed cookstove with chimney can remove the smoke from the kitchen properly and suggested that this data could be used as the benchmark for the comparison of improved cookstove performance with the traditional cookstove models.

3.2. Design methodology

The earlier cookstoves were fabricated by development workers on site in developing countries including India using locally available material and resources. These stoves were fabricated according to the requirement of local households without any scientific knowledge and any quality control [45]. An improved cookstove can be defined as a stove that needs less biomass to cook the same amount of food than a traditional one and consequently produces less smoke than a traditional stove [46]. Few researchers [29–33,45] studied the processes inside a cookstove and evaluated the design principles for improved biomass cookstove and most of them have been covered in this article. The biomass cookstove is a complex engineering device [29] which involves two major phenomena named as combustion and heat transfer.

3.2.1. Combustion of fuel

The combustion process plays a great role in a cookstove design and performance. The solid fuel combustion is a much more complex than the liquid or gaseous fuel combustion due to the processes of pyrolysis. Generally, the solid fuel combustion takes place in two stages: flaming combustion of volatiles and glowing combustion of char. The char combustion in a cookstove depends on the surface area exposed of the fuel piece, the way a bed laid out, rate of pyrolysis and fluid flow through the fuel bed. The shape of the combustion chamber, cross-sectional area, height and volume are the important parameters for the design of any combustion chamber using a solid fuel. The fuel burning rate is determined by the size of a grate and in the case of a stove without grate determined by the diameter of the combustion chamber. The height of the combustion chamber should be related to the flame height [29]. The phenomenon of combustion [32] can be explained as below:

- At about 100 °C, conduction of heat in the wood takes place due to which the absorbed water boils and migrates along the wood grain to cooler areas and re-condenses. At slightly higher temperatures, the water binds to molecular groups also evaporates. At about 200 °C, as the temperature increases, hemicellulose begins to decompose followed by cellulose and the decomposition becomes considerable higher at around 300 °C. About 8–15% of cellulose, hemicelluloses and roughly 50% of the lignin remain as fixed carbon. The remaining is released as volatile gases. The volatiles produced by this decomposition, may escape as smoke.
- As the volatiles escape from the wood, they mix with oxygen and burn at about 550 °C, due to which ignition produces a yellow flame. The radiant heat from the flame also plays a crucial role in maintaining the combustion process. The rate of combustion is controlled by the rate at which these volatiles are released. The small pieces of wood due to large surface area absorb more radiant heat, and thus, have more rate of release of volatiles. Thus, the fires with small pieces of wood tend to burn quickly than the larger pieces. As the amount of volatiles rises, they react with other volatile molecules and form soot and smoke. Simultaneously, burning of volatiles takes place as they mix with oxygen molecules.
- The temperature of the hot gas produced from the wood is typically of around 1100 °C. It is limited by radiant heat loss and by mixing with cold ambient air. The burning volatiles account for about two-thirds of the total energy released by a wood-fire. If a cold object is placed close to the fire, it will cool down and stop the combustion of some of these volatiles, thus, will leave a thick black smoke. The volatiles are released as long as the wood is hot. If the air supply is stopped, the combustion process will also stop down. The heat output of the fire is reduced but the wood continues to be consumed as long as it is hot. The unburned volatiles release as smoke and the charcoal remains behind as residue.
- As the topmost layers of wood gradually lose all their volatiles and thus, only a porous char remains. This hot char helps to catalyze the breakdown of escaping volatile gases, produces

lighter and more completely reacting gases to feed the flames. In some cases, the volatiles cannot easily escape through this char layer. The volatiles expand and force their way out. Thus, they are the cause for the burning wood cracks and hiss. The char layer also has a lower thermal conductivity than wood. This decreases the conduction of heat to the interior and thus, slows down the release of volatiles to feed the flames. At the surface of the char, carbon dioxide reacts with the char's carbon to produce carbon monoxide. Slightly away from the char surface, the greater concentration of oxygen completes the combustion of combustible gases by reacting with the carbon monoxide to produce carbon dioxide and heat.

- The temperature near the surface of the burning charcoal is typically of about 800 °C. The endothermic (heat absorbing) dissociation of carbon dioxide to carbon monoxide and oxygen, the radiant heat loss limits the higher temperatures of char. When all the carbon has burned off, only the mineral salts remain as ash. The ash limits the flow of oxygen to the interior surface of wood and hence, limits the combustion rate, which is an important mechanism to control the combustion rate in the charcoal stoves. A wood-fire burning at a power level of 1 kW burns 0.0556 g of wood/s (calorific value of wood is around 18 MJ) and requires about 0.278 l of air/s. However, excess air is very important to ensure the complete combustion of the wood-fuel in most of the applications.

3.2.2. Heat transfer

It is well known that the heat transfer is an important phenomenon in a cookstove and it is helpful to transfer heat to the cooking pot by the combustion of wood. Due to the different losses, thorough study of different heat transfer processes is very important and necessary to understand the mechanism of heat transfer in a cookstove. The study of different heat transfer processes in a cookstove is described by Baldwin [32] and others [2] as discussed below:

- **Conduction:** In a solid material, heat is conducted by vibrating atoms and they speed up the vibration rate of more slowly moving neighbor atoms. In metals, heat is conducted by free electrons, which move with a high velocity from high temperature regions to lower temperature regions, where they collide and excite atoms. For a cookstove, the different areas in which the heat transfer through conduction takes place, are shown in Fig. 2(a) and can be written as below:
  i. The transfer of heat from the cooking pot to the cooking material of the pot;
  ii. The heat losses through the stove wall;
  iii. The heat storage from the flame to wood; and
  iv. The heat storage in the pot material and in the stove body [2]. Larger the mass and specific heat of an object, the more energy it can store for a given change in temperature. Thus, a massive stove warms up slowly while a lightweight stove warms up rapidly [32].
- **Convection**: Convective heat transfer occurs, when a gas or liquid flows naturally or forced into a region at a different temperature and exchange heat energy through conduction by the interaction of individual particles [32]. In a cookstove the areas to be taken into consideration for convective heat transfer are shown in Fig. 2(b) and can be written as below:
  i. The hot gas plume from the fire;
  ii. The jet along the pot bottom and/sides, where the hot gases flow outward and upward;
  iii. The flow through tunnels, chimney, over baffles, and in the gap between the pot and wall; and
  iv. Outer surfaces of pots, stoves and chimney.
- **Radiation**: All materials emit greater amount of radiation energy in the form of electromagnetic radiation due to the internal molecular and atomic motion because of its higher temperature. The different areas for radiation losses to be taken into consideration, while, designing an improved cookstove are shown in Fig. 2(c) and can be written as below:
  i. The radiation emitted from the flame;
  ii. The radiation exchange between the inner walls, pot and the wood surface; and
  iii. The radiation loss to the atmosphere from the wall, pot, chimney, and the opening of the combustion chamber [2].

Verhart [45] analyzed the cooking processes and energy requirements that take place generally, in a household such as boiling, frying, baking, and grilling in “on designing wood-stoves”. He presented a discussion on the building materials, heat transfer mechanism and energy supply options and discussed the role of natural draft for improving the combustion and heat transfer modes in a cookstove. He also recommended some important points to improve the combustion efficiency of the cookstove. It was suggested that for complete combustion of small pieces of fuel, certain points should be considered. Some of them are mentioned as below:

i. The complete combustion of volatiles should be ensured before its interaction with fresh charged new wood piece;
ii. Initially, the primary air should be regulated to ensure a char combustion rate of about 13.5% of the designed power output of the cookstove.

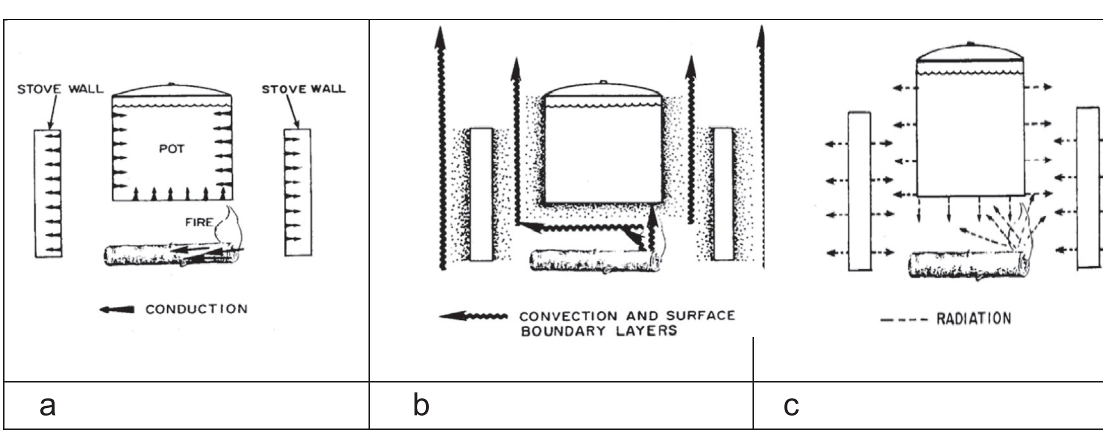


Fig. 2. Different heat transfer processes in a cookstove [32].

iii. At the end of volatile combustion, the rate of air supply should be increased to get more power output from the char.

Baldwin [32] described few techniques related to engineering design, development, and dissemination of the improved biomass cookstove to improve the combustion quality and heat transfer rate. Some of the points are described as below:

i. The stove performance can be improved by introducing a grate because it performs several functions such as injecting air below the fuel bed for better mixing of air, which is required for proper combustion of fuel. This will increase the thermal efficiency and reduce the emissions from the cookstove.
ii. The cookstove efficiency can be increased by controlling air flow into the combustion chamber. Also an optimum flow rate not only enhances the efficiency and combustion temperature but also reduces the emissions, which is also a very important parameter.
iii. The preheating of incoming air may also improve the quality of combustion, in other words, it may achieve complete combustion and better thermal efficiency by raising the average temperature of the combustion chamber.
iv. The shape of the combustion chamber should be optimized because it affects the combustion quality and stove efficiency.
v. Also, a good insulation inside the combustion chamber raises the interior temperatures and thus, reduces the emissions.

Winiarski [31] developed the design principles to improve the combustion and heat transfer efficiency of wood burning cookstove, as shown in Fig. 3. On the basis of these design principles, the famous rocket stove was designed and fabricated as shown in Fig. 4. Some of the designed principles described by Winiarski [31] are as mentioned below:

i. Heat and burn the tips of the sticks only;
ii. High and low heat can be created by number of sticks put into the burning fire;
iii. There should be constant cross-sectional area throughout the cookstove;
iv. The wall of the cookstove should be well insulated.

Guzman and Jordan [47] stated that the thermal efficiency of an improved cookstove depends upon two simultaneous processes firstly, the combustion of the fuel and secondly, the heat transfer process. The combustion efficiency is a ratio of thermal/heat energy which is produced by the combustion of fuel to the total

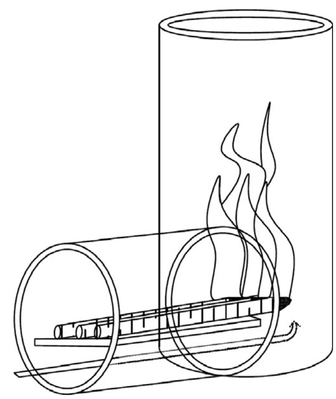
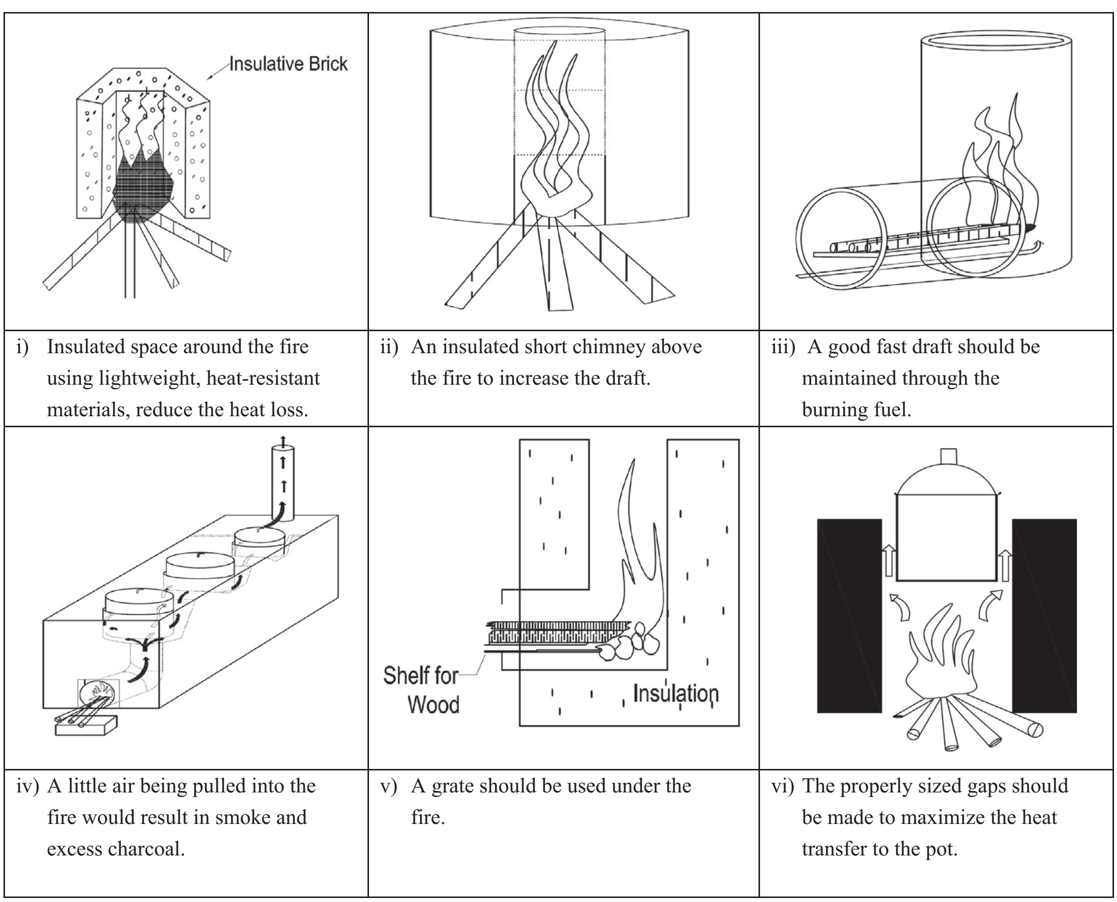


Fig. 4. The rocket stove design [31].



i) Insulated space around the fire using lightweight, heat-resistant materials, reduce the heat loss.

ii) An insulated short chimney above the fire to increase the draft.

iii) A good fast draft should be maintained through the burning fuel.

iv) A little air being pulled into the fire would result in smoke and excess charcoal.

v) A grate should be used under the fire.

vi) The properly sized gaps should be made to maximize the heat transfer to the pot.

Fig. 3. Winiarski's design principles [31].

thermal/heat energy available in the fuel, while, heat transfer efficiency is a ratio of energy, which is delivered to the cooking pot to the total heat produced by the combustion of wood. The combined efficiency of both processes decides the overall efficiency of the cookstove as follows:

$$\eta_o = \eta_c \times \eta_{ht} \tag{1}$$

where, η_o is the overall efficiency of the cookstove, η_c is the combustion efficiency and η_{ht} is the heat transfer efficiency. The thermal efficiency can be determined by the following equation:

$$\eta_f = \frac{Q_t}{Q_w} \tag{2}$$

where, Q_w is the total thermal energy available in the wood and Q_t is the heat utilized.

Reed [33] described the Top-Lit Up-draft (TLUD) micro-gasification principle for designing and fabrication of the gasifier and pyrolytic stove shown in Fig. 5. A gasifier stove has the potential to offer biomass as a clean cooking fuel through clean combustion of biomass, where the charcoal and fire-wood became a rare and expensive. This simplest TLUD has the separate entry holes for primary and secondary air. The proper mixing of the gaseous fuel (i.e. volatile matter) with oxygen takes place with the help of secondary air to ensure proper and complete combustion. A chimney above the combustion zone creates draft and further enhances the mixing of gas and oxygen. The options for providing adequate primary air depend on fuel size. For example, for thin fuel pieces natural draft is sufficient, whereas, for thick fuel pieces, air needs to be forced through the fuel bed and the easiest to provide it by using a small fan or blower. Also the current research is taking place using thermo-electric generators and photovoltaic panels to produce electricity for lightening and to run a small fan for forced draft cookstoves [48–50].

Yuntenwi et al. [51] studied the effect of wood-fuel moisture on heat transfer and combustion efficiencies of the three stoves namely, open fire, the Chinese rocket stove and the modified single walled VITA stove, respectively. These stoves were tested at a moisture content of 5%, 15% and 30% (wet basis), respectively. The results show that there is an optimal value of moisture content at which the thermal efficiency attains the highest value, this is because of the fact that the combustion was found to be lower at the extremely dry and over-wet fuel conditions. They concluded that the type of stove also exhibits a stronger effect on the total emissions from the cookstove besides, the moisture content of the fuel. As various factors affect the efficiency of a cookstove, firstly the theoretical model is prepared as described in next section and then the different tests will be performed. This method will be beneficial in terms of economy and resources management leading to better performance in all respect. Based on the design parameters mentioned above, the detailed mathematical modeling needs to be developed for better understanding of the cookstove devices. The detailed mathematical modeling along with kinetics and effects of various design parameters of different cookstoves is elaborated in the next section.

3.3. Mathematical modeling

Improved biomass cookstoves have the ability to reduce indoor air pollution, deforestation, climate change, and improve quality of life on a global scale. The better design of these cookstoves can significantly impact their performance and emissions. Although, these improved biomass stoves have been studied for a long time. However, a theoretical understanding of their operating behavior and the development of engineering tools for an improved cookstove based on natural convection is still lacking. This section presents the mathematical modeling of improved biomass cookstove based on various performance parameters.

3.3.1. Side feed wood-burning cookstove

Agenbroad et al. [52] developed a simplified model for understanding the fundamental operating behavior of the natural convection based biomass cookstoves. The model was developed by using the dimensional form of the two-equations system. This model has been further developed into a dimensionless form at a later stage [53]. A simplified model of the fundamental stove has been developed for predicting bulk flow rate, temperature and excess air ratio, based on stove geometry including chimney height, chimney area, heat release losses and the operating firepower. The stove operator decides the operating firepower of the stove by controlling the fuel feed rate and excess air ratio. The resulting bulk flow rate, temperature, and excess air ratio, etc. are the fundamental inputs for stove performance. The analytical stove flow model and the one dimensional flow model are shown in Figs. 6 and 7, respectively.

The processes are categorized into two basic and fundamental processes: (a) heat addition from combustion (at state point 2), and (b) kinetic energy addition (between, state points 1 and 2) due

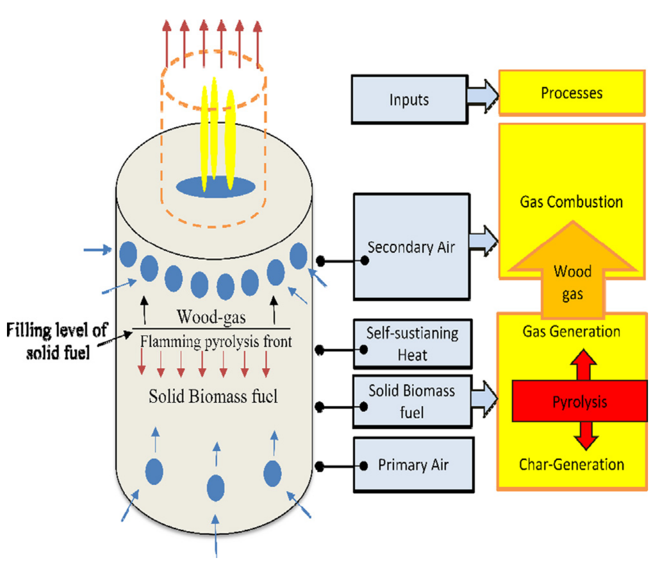


Fig. 5. Top-Lit Up-draft (TLUD) micro-gasifier principle [32].

Fig. 6. Insulated rocket elbow stove [53].

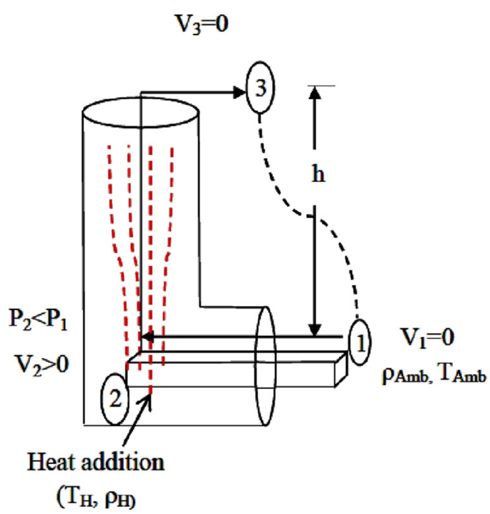


Fig. 7. Simplified model setup [53].

to the chimney effect as shown in Fig. 6. These processes are described as below:

- **Heat addition from combustion**
  The heat of combustion increases the temperature and decrease the density of bulk flow pass over there. If we assume that the heat addition is efficient and instantaneous at point 2 and the system is isobaric with no mechanical work done on/by the system, the gas flow will behave like the ideal gas with constant potential and kinetic energies. The heat addition from the combustion showed an increase in the enthalpy (h_C to h_H) distributed in the mass flow rate ($\dot{m}_A$). The increased bulk flow temperature is calculated for a given mass flow rate ($\dot{m}_A$) and heat release rate ($\dot{Q}_{in}$), using the constant pressure specific heat of air (C_p), as below [52]:

$$\dot{Q}_{in} = \dot{m}A(h_H - h_C) = \dot{m}A \int_{T_C}^{T_H} C_p(T)\, dT \tag{3}$$

  where, T is the bulk flow temperature and the subscripts H and C denote the hot and cold conditions, respectively.
- **Kinetic energy addition due to the chimney effect**
  The air flow through the stove depends on the chimney effect, resulting from the buoyant force of the decreased density of air after heat addition of combustion. The decreased density of air in the chimney between points 2 and 3 creates a lower pressure at state point 2 as compared to the ambient pressure at state point 1. In a fluid, the relationship between pressure variations with depth can be determined using the hydrostatic equation and the net pressure difference (ΔP) as

$$\Delta P = g \int \rho(h) dh \tag{4}$$

  where, g is the acceleration due to gravity and ρ is the density of medium, which is a function of chimney height (h). The pressure at state points 1 and 2 can be calculated as below:

$$\Delta P_{1-2} = \left(P_3 + g\int_3^1 \rho_{amb}\, dh\right) - \left(P_3 + g\int_3^2 \rho(h) dh\right)$$
$$= g\rho_{amb} h - g\int_3^2 \rho(h) dh \tag{5}$$

  If chimney walls are assumed to be adiabatic, than the temperature and density, ρ of the flue gases in the chimney (T_H and ρ_H) remains constant, so Eq. (5) can be simplified as

$$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) \tag{6}$$

  The gain in kinetic energy of the chimney flow at state point 2 from the stagnant ambient air at state point 1 can be calculated using the integral form of Bernoulli's equation for the compressible flow as

$$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H v_2^2 \tag{7}$$

  where, ρ_H is the density of hot gas and v_2 is the velocity at state point 2. Assuming the ideal gas behavior of the flue gases, the density is also related to the temperature. Thus, using ideal gas equations and solving Eq. (7) for volume and mass flow rate, yields

$$gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H \left(\frac{\dot{V}}{A}\right)^2 \tag{8}$$

$$\dot{V} = CA\sqrt{2gh\frac{\rho_{amb} - \rho_H}{\rho_H}} \tag{9}$$

$$\dot{V} = CA\sqrt{2gh\frac{T_H - T_{amb}}{T_{amb}}} \tag{10}$$

$$\dot{m}_A = CA\left(\frac{P}{R_s}\right)\left(\frac{1}{T_H}\right) \times \sqrt{2gh\frac{T_H - T_{amb}}{T_{amb}}} \tag{11}$$

  where, C is the loss coefficient, introduced to account for uncertainties and inefficiencies in the chimney effect. This includes the viscous losses, chimney wall heat transfer, and the unrealistic ideal point heat addition at state point 2 and its range is $0 \le C \le 1$. The mass flow rate of fuel ($\dot{m}_F$) in the cookstove model can be calculated from the firepower ($\dot{Q}_{in}$) and the heating value (HV) of the fuel, as below

$$\dot{m}_F = \frac{\dot{Q}_{in}}{HV} \tag{12}$$

  The air fuel ratio (AFR) and excess air ratio (EAR) can be determined as below:

$$AFR = \frac{\dot{m}_A}{\dot{m}_F} \tag{13}$$

$$\Phi = \frac{AFR_{stoich}}{AFR} \tag{14}$$

$$\%EAR = \frac{(1-\Phi)100\%}{\Phi} \tag{15}$$

  where, AFR_{stoich} is the air furl ratio (AFR) for stoichiometric combustion. The lower heating value (LHV) is used because the latent heat of the water vapor is significant, and seldom recovered.
- **Dimensionless chimney effect equation**
  The advantage of working in the dimensionless form includes the scale similarity, reducing the number of independent parameters for experimentation, and thus, it is independent to the stove geometry. The dimensionless temperature form can be determined by inspection, as below:

$$T^* \equiv \frac{T_H - T_{amb}}{T_{amb}} \tag{16}$$

  Using Eqs. (11) and (16), the mass flow rate of air in the cookstove model can be written as

$$\dot{m}_A = CA\left(\frac{P}{RT_{amb}}\right) \times \frac{\sqrt{2ghT^*}}{(T^*+1)} \tag{17}$$

Substituting (P/RT_{amb}) as the ambient density ρ_{amb} in the above equation and rearranging it as

$$\frac{\dot{m}_A}{CA\rho_{amb}\sqrt{gh}} = \frac{\sqrt{2T^*}}{T^*+1} \tag{18}$$

This dimensionless mass flow rate can also be defined as the ratio of the actual mass flow rate to the characteristic natural convection and the dimensionless mass flow rate of air for the given geometry can be written using Eq. (18) as

$$\dot{m}_A^* \equiv \frac{\dot{m}_A}{CA\rho_{amb}\sqrt{gh}} \tag{19}$$

The final form of the chimney effect equation can be written using Eqs.(18) and (19) as

$$\dot{m}_A^* = \frac{\sqrt{2T^*}}{T^*+1} \tag{20}$$

- **Dimensionless heat addition equation**
  In the dimensionless heat addition equation, the mass burn rate of fuel is used instead of the firepower. Using Eq. (12), the relation between the firepower, mass burn rate, and heating value is given as below

$$\dot{Q}_{in} = \dot{m}_F HV \tag{21}$$

Substituting Eqs. (21) and (16) into Eq. (1) yields a dimensionless heating value group (HV*) as

$$\dot{m}_F\left(\frac{HV}{C_pT_{amb}}\right) = \dot{m}_A T^* \tag{22}$$

$$HV^* \equiv \frac{HV}{C_pT_{amb}} \tag{23}$$

This group (HV*) can be defined as the ratio of the combustion heating energy (HV) to the initial thermal energy of the flow (C_pT_{amb}). On substituting the dimensionless mass flow rate of air from Eq. (19), into Eq. (22), gives the relation between dimensionless heating value, the dimensionless mass flow rate of air and dimensionless temperature as below

$$\dot{m}_F HV^* = \dot{m}_A^* CA\rho_{amb}\sqrt{gh}T^* \tag{24}$$

A dimensionless mass burn rate similar to the dimensionless air flow rate of Eq. (19), can be written as

$$\dot{m}_F^* \equiv \frac{\dot{m}_F}{CA\rho_{amb}\sqrt{gh}} \tag{25}$$

Using the dimensionless mass burn rate of fuel ($\dot{m}_F^*$), the final form of the dimensionless heat addition equation becomes

$$\dot{m}_F^* HV^* = \dot{m}_A^* T^* \tag{26}$$

- **Air/fuel ratio from the dimensionless model**
  The air/fuel ratio (AFR) is defined as the ratio of mass flow rate of air to the mass burn rate of fuel and can be given by rearranging Eq. (26) as

$$AFR = \frac{\dot{m}_A^*}{\dot{m}_F^*} = \frac{HV^*}{T^*} \tag{27}$$

The dimensionless heating value (HV*) is considered as remain constant throughout the stove operation. From the above equation, a simple inverse linear relationship can be seen between dimensionless temperature (T^*) and the air fuel ratio (AFR). Based on the above (theoretical) model, an actual model can be prepared, which may provide a better thermal efficiency than that of the traditional cookstove.

3.3.2. Pulverized fuel stove

The firewood is considered as a better fuel amongst the different varieties of biomass, which are easily available. Other agricultural residues, such as, mustered straw are used only, if the firewood is not available. However, fine agricultural residues and tree droppings including leafy biomass pose technical problems and hence, it is very difficult to use this type of biomass as the domestic fuel. Other agro-residues have many problems, such as, they are small in size due to which they burn up faster, give fluctuating power levels and therefore, require much greater periodicity in feeding with more attention. The loose biomass burns up faster and emits more products of incomplete combustion compared to solid biomass. The various bio-fuels such as wood and crop residues are not significantly different in their structure and energy content. Thus, the pulverization would convert these multiple fuels into common physical form with possibility of controlled combustion and they can be used in stoves like sawdust. In the case of sawdust, a stove has been designed several decades ago in many countries. This stove is also called the tube stove as shown in Fig. 8(a). As the simple tube stove was based on combustion mode and was not thermally efficient and hence, the new concepts of single-port and multi-port pulverized stoves (see Fig. 8(c)) based on gasification mode were developed at later stage [54]. The typical configuration of a single-port and multi-port pulverized fuel stove air inlet(s) at bottom and top were also provided.

Dixit et al. [54] developed a single-port pulverized fuel stove with improved thermal efficiency and lower emissions at constant power level. Their design was based on a cylindrical sawdust stove with a central port hole to be fitted at the bottom. They achieved the stable premixed combustion behavior of the combustible gases by the use of air supply through a thin slot at the bottom. They conducted their studies on single-port design configuration to extend the gasification duration, stable power level and had an air entry from the bottom to control the air flow. The stove exhibited conversion efficiency of 37% due to good flame at exit. The emission factor for CO and NO_x was about 12 g (kg-fuel)$^{-1}$ and 1 g (kg-fuel)$^{-1}$ respectively.

3.3.3. Wood gas stove

Panwar and Rathore [55] presented the design criteria, safety measures and operating procedure of a wood gas stove. This model was based on the biomass gasification principle and worked on natural draft mode. They found that the thermal efficiency of that stove was about 26.5%. It could be operated with very low emissions and could utilize a wide variety of biomass fuels. They also stated that the wood gas burnt with a blue flame having flame temperature of about 736 °C. They had taken the diameter and height of the stove as 16 cm and 41.5 cm, respectively. The cookstove was designed in the following manner:

The amount of energy (Q_n) to cook food for a family of six members taken was as of 15.8 MJ. The fuel consumption rate (FCR) was determined by taking the calorific value (CV) of babul wood as of 15.5 MJ kg^{-1}, while the gasification efficiency was taken as of 70% and by using the following equation:

$$FCR = \frac{Q_n}{CV \times \eta_g} \tag{28}$$

where, Q_n is the energy need, η_g is the gasification efficiency in percentage, CV is the calorific value in MJ kg^{-1} respectively. The reactor diameter (D) and height (H) are calculated using the

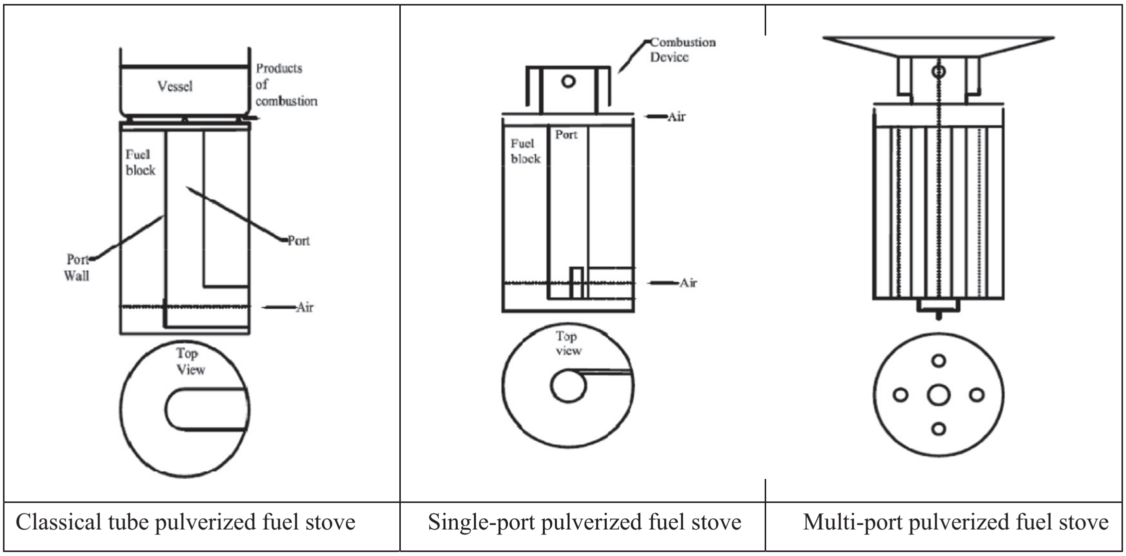


Fig. 8. Different types of pulverized fuel stoves [54].

following relations:

$$D=\left[\frac{4FCR}{\pi SGR}\right]^{1/2}=\left[\frac{(4/\pi)FCR}{SGR}\right]^{1/2}=\left[\frac{1.27FCR}{SGR}\right]^{1/2} \tag{29}$$

$$H=\frac{SGR\times T}{\rho_{wood}} \tag{30}$$

where, SGR is the specific gasification rate in kg^{-2} h^{-1}, ρ_{wood} is the wood density in kg m^{-3}, T is the duty hour, Q_n is the energy need in MJ h^{-1}, and FCR is the fuel consumption rate in kg h^{-1}. Based on the above models, an improved biomass cookstove can be designed and fabricated.

4. Impact on environment and health

The consumption of biomass is very large in developing countries due to the fact that the biomass fuels are readily available everywhere and can be burnt directly for cooking and heating purposes [56]. They are usually cheaper and have no monetary cost like other fuels. Therefore, this is the primary source of energy in the developing countries. But the biomass fuels are usually burnt in open-fire three-stone and traditional cookstoves in kitchen/rooms without proper ventilation. Thus, it contributes to the high levels of harmful emission products inside the house/kitchen causing severe health problems in women and children and affects the environment [34,57] because woman has the responsibility of cooking for family members [58]. With the increasing awareness about the negative health impacts due to emissions from solid biomass cooking fuels among the scientific community, the rigorous research on emissions reduction, deforestation, health and social issues, etc. has been started during the early 1990s [6]. The initial objective was to minimize the direct exposure to the exhaust/flue gases, decreasing the fuel consumption, thereby, saving the time spent on biomass fuel collection by female child and women, besides, to make the biomass cookstove acceptable for the billions of people who were relying on it to satisfy their daily needs. Currently with the raising awareness about the cooking related issues among different countries, three important issues deforestation, climate change and health due to green house gas emissions (GHG) emphasized and a number of authors have studied these issues in detail [70,76,84].

4.1. Deforestation

Since, wood fuel gathering was thought to be the primary cause of deforestation in the different regions, the improved cookstoves have been long known as a major imperative for reducing deforestation. Karekezi and Turyareeba [25] studied the efforts for dissemination of improved cookstoves by different NGOs, Governmental agencies, and institutions in Eastern Africa. It has been stated that the household smoke concentrations due to traditional stoves have a great cause for health concerns, and to decrease energy crisis. The importance of the energy efficiency of improved stoves is alleviated that is self-evident. Since, the fuel wood has been seen as a fuel with many advantages and included cultural considerations and hence, the fuel wood could not be replaced entirely, even in households that had been using modern fuels for many years. Agarwal [59] presented the difference in approaches for diffusion of innovations in rural areas because innovations differ from one another in terms of technical, economical and social characteristics, which provides the analytical framework for improved wood burning stoves. The promotion of improved wood burning stoves was being widely sought as an essential component of the strategy for reducing the 'wood-fuel crisis', which has been faced by many countries. However, those stove diffusion programs were ineffective, either in the adoption or in the required saving of wood. They suggested that the diffusion of wood-burning stoves requires a different approach from the usual 'top-down' method. They noted that the process of innovation i.e. designing of a cookstove need to be linked integrally to that of the diffusion. Also whether or not the stove was adopted, or continued to be used when adopted this needs to be determined by the user's involvement in the design process.

Ramakrishna et al. [22] stated that in the developed countries, the transition to cooking stoves using clean fuels took place as a natural consequence of the economic development. Masera and Navia [60] studied the fuel wood used and inter-fuel substitution in three villages of the Purepecha Highlands, Mexico. They showed that: (a) Mexican rural households followed a multiple-fuel used strategy both LPG and fuel wood; (b) the process of inter-fuel substitution has a definite pattern based on the cooking tasks, and (c) the fuel-wood demand did not disappear as fast as predicted on a pure fuel switching or fuel transition approach. Their analysis showed that energy and fuel-wood savings were much lower than that expected value, which was on a purely technical basis.

They concluded that the households followed a multiple fuel strategy, which gave them the advantage of both fuels and also there was a strong pattern of fuel preferences depending upon the type of dish and cooking task to be performed by the end-user.

The socio-economic and environmental consequences of wood fuel usage in the traditional cooking stove in floodplain rural areas in Bangladesh was studied by Miah et al. [61]. They conducted a study on traditional cooking stoves to determine the structural characteristics and amount of wood fuel consumed using a multi-stage random sampling. Alam and Chowdhury [62] evaluated the economical, ecological and socio-cultural achievements of improved earthen stoves that were provided to the beneficiaries under a project to improve biomass energy utilization. The improved earthen stove had been distributed for free of cost to the beneficiaries under a project component of Sustainable Environment Management Program of the Ministry of Environment and Forest of the Government of Bangladesh. Providing improved earthen stove to the women beneficiaries was an input among others in course of project implementation. The energy saving through improved earthen stove has brought several changes and improvements in fuel usage, economic, environment and socio-cultural aspects. The introduction of improved stove was a safer, cost saving and proven technology that fulfilled the needs of the end-users. The fuel savings reduced outlays for purchasing wood, shortened collection times, alleviated local pressure of fuel resources and diminished air pollution up to a significant level.

Torres-Rojas et al. [63] studied on-farm biomass production to meet the energy needs of households in Western Kenya. They suggested that the pyrolytic or improved combustion cookstoves should be used instead of the traditional cookstoves. The variability of biomass production was high in that region but biomass could not be harvested and used sustainably due to various reasons. They concluded that the households could use combination of different biomass to meet their cooking energy needs through pyrolytic cookstoves, due to the fact that a wider range of feedstock could be utilized. This could be helpful not only in reduction of overall energy consumption, making women less reliant on wood and biomass fuel, thereby, decreasing the time spent in the collection of wood biomass from other sources, thus, sparing more time for other productive activities. In addition, to increase overall food production for the households, the production of biochar and its use as a soil conditioner could be increased on-farm crop productivity.

Ayoub and Brunet [64] carried out laboratory tests to analyze the performance of traditional three stone open-fire cookstove against a large-sheet metal fuel-wood cookstove designed for community kitchens. The standard water boiling test was performed for both cookstoves and the percentage of heat utilization, firepower and the specific fuel consumption were calculated. They found that the metal cookstove was three times more efficient and consumed only one fifth of the energy to boil an equivalent amount of water than that of the open-fire cookstove. They noticed an appreciable savings in fuel-wood consumption, collection time, and thus, its purchase costs. Besides, the tangible health and social benefits using the cookstoves were also enumerated. Also, the suggestions for simplifying the stove fabrication process, improving field dissemination, and creating a possible cottage industry were proposed. Quadir et al. [65] tried to identify the barriers in dissemination of renewable energy technologies for one of the most important end-uses of energy, i.e. cooking. An effort was made to provide some insight regarding the issues and factors that are likely to affect the adoption of three prominent renewable energy technologies for cooking, namely biogas plants, improved biomass cookstoves and solar cookers.

Gupta et al. [66] stated that the prolonged and uninhibited use of biomass fuels for over thousands of years had resulted in massive deforestation all over the world. This in turn, caused an increased shortage of biomass fuel for cooking besides creating pressure on the households relying on the same. However, these households could not be shifted toward cleaner fuels due to economic constraints and hence, continued using whatever biomass fuels they could get free and/or at a cheaper price without thinking about the harmful health impacts, while, burning these fuels in traditional cookstoves. Biomass smoke from combustion contains a wide range of pollutants which could prove to be extremely health damaging due to continuous exposure. They also concluded that to eliminate the indoor air pollution using improved cookstoves and cleaner fuels were too expensive for the majority of people to be adopted, due to the fact that majority of people belong to the poor section of the society. They also suggested that search for better species of non-woody biomass fuels should be carried and to be verified by laboratory experiments, which could be introduced to the end-users to lessen the extent of the indoor-air pollution problem. This may also be taken into consideration through international funding agencies such as GEF, IFC, carbon finance, etc.

Muneer and Mohamed [67] studied the adoption rate of the improved cookstove in Khartoum State, which has the highest consumption of charcoal and firewood in Sudan. They also attempted to explore the factors that influence the households' innovativeness regarding adoption of improved cookstoves. Their study suggested that the male head of the household is not the sole decision-maker in all of the household's affairs and issues in Sudan. This emphasized the importance of analyzing each social system in terms of the decision-making process, division of labor, and gender relations. But not relying on generalizations in the literature, when planning for dissemination and adoption of innovations, particularly in the developing countries. They also suggested that a small group at a particular location should be targeted for sustainable and smooth dissemination of improved cookstove as an initially experiment based on the observation, experience, and findings.

Pokharel [68] examined the pattern of energy use for cooking in an urban area of Nepal including energy characteristics for cooking, obtained from laboratory tests, besides, the energy use cost (EUC) for various cooking alternatives. He emphasized that the actual cost of energy use depends upon the cost and the material properties of cooking utensils. For example, to cook rice, which is a fast-cooking food item, thinner utensils are better while, for slow-cooking items such as lentils and beans, thicker utensils are better. Mainly, due to the fact that they have good heat retention and uniform heat distribution (to food) capabilities. If a stove used to cook a food item in two different utensils for the same time period, fuel-use cost (FUC) would be the same but the actual cost of energy use would be different because costs and heat absorption capabilities of different utensils are different. This type of energy-use cost (EUC) is referred as useful energy-use cost (UEUC) and would be considered for cost comparison of various energy alternatives. He also examined the community and household factors that affected the initial adoption of improved cookstove lead to sustainable dissemination and usage of cookstove. However, no detailed tracking report of stove adoption and usage patterns over extended time period could be prepared through home visits. It was also stated that the ongoing social and behavioral processes of adoption of improved biomass cookstove must be understandable. The full benefits of cookstove dissemination programs cannot be identified or estimated in any region/state of any country.

Kathleen et al. [69] identified the household and community characteristics associated with early adoption of Patsari stoves including the factors that lead to sustained use over time, by

tracking of stove adoption and usage patterns over an extended time periods through repeated home visits. Further, a bi-level approach was proposed that may be used for stove dissemination programs to target early adopter communities and households for stove dissemination in order to increase the adoption rates within communities. Hence, the improved cookstove adoption rate is an important criterion for the decreased fuel consumption, environmental pollution besides, to tackle the deforestation.

4.2. Effect on climate

The manner in which fuel is harvested has a large influence on the climate change potential. If biomass is harvested sustainably, the CO_2 released due to combustion will theoretically be reabsorbed by the biomass growing to replace it. However, if biomass is not harvested sustainably, the CO_2 which is released during the combustion of biomass will thereby contribute to the build-up of CO_2 in the atmosphere. The products of incomplete combustion such as carbon monoxide, methane, and particulate matter contribute to the changing of the climate. The large-scale use of cleaner cookstoves might reduce the global warming up to certain extent. Different studies carried out so far by number of authors are summarized here to describe the effects of biomass cookstove on the environment, as below:

4.2.1. Green house gases

Edwards et al. [70] presented the emissions database from cooking stoves for 23 typical fuel/stove combinations tested in a simulated village house in China. They observed the pollution level, enhanced due to poor combustion efficiency of biomass cookstove, thereby, contributing to green house gases and thus leading to the global warming. Besides, a significant portion of fuel carbon goes waste as a result of poor combustion. They also concluded that due to the approximately linear decrease in combustion efficiency, there was an increase in emission of products of incomplete combustion. On the basis of above observations, they developed a linear model to predict the emissions of green house gases and health damaging pollutants, which were linked to carbon dioxide (CO_2) and products of incomplete combustion (PIC) and hence, predicted the global warming contributions from residential cookstoves in China.

MacCarty et al. [71] studied the relative emissions from five common types of biomass cookstoves. Their results showed that in sustainable harvesting situations, where CO_2 emissions were considered neutral, some improved cookstoves with rocket-type combustion or fan assistance could reduce overall global warming impact from the products of incomplete combustion (PICs) by 50–95%. In nonsustainable situations where thr fuel and CO_2 savings were of greater importance, three types of improved combustion methods have shown the potential to reduce the global warming by 40–60%. Although, the charcoal-burning devices emitted less CO_2 than the traditional wood-burning, yet the emissions from incomplete combustion were found to be significantly greater than the traditional cookstoves.

Zhang et al. [72] presented a systematic study of trace gases (CO, CO_2, NO, NO_2, and NO_x) and particulate matter from rice, wheat and corn straw, which are the major agricultural residues in China. They had performed their experiment by burning the above mentioned residues in a typical cookstove and aerosol chamber of Fudan University (ACFU) in Shanghai. They also discussed the emission factors, inventory and allocation of gaseous pollutants from the burning of rice, wheat and corn straws at regional and global levels in China.

4.2.2. Black carbon

Johnson et al. [73] estimated the potential reductions in emission of gaseous and aerosol greenhouse species that would result from replacing a traditional open-fire stove with an improved "Patsari" cookstove in rural Mexico. In addition to a reduction in overall particulate emissions from rural homes during daily activities, the ratio of organic carbon to that of the elemental carbon decreased between the open-fire and improved Patsari cookstoves. However, the overall elemental carbon contribution for the Patsari cookstove could be reduced, while, the fraction of elemental carbon increased relatively to that of the organic carbon.

Grieshop et al. [74] analyzed the impacts by replacement of 'traditional' cookstoves with different improved cookstoves on health and climate. They observed that health and climate impacts of available household cooking options in developing countries vary sharply. They analyzed and compared the health, climate impacts and the potential co-benefits from the use of fuel and stove combinations. They stated that the indoor air pollution and climate are influenced by the combustion performance, ventilation and fuel properties. They also concluded that the emission components, which were not included in the current carbon trading schemes, such as, black carbon particles and carbon monoxide, could contribute to a larger proportion of the climate change and global warming. Finally, they observed that the improvements in the biomass cookstoves could be improved the indoor air quality, which nonetheless remains significantly higher as compared to those of clean fuel cookstoves like LPG.

Simon et al. [75] reviewed the possibilities of climate and local developments due to improved cookstoves distribution programs that use the carbon revenues. They stated that if improved cookstoves used continuously could play an important role in local development and global climate change. They also described a number of barriers such as cultural, financial, governance, and technological to achieve win–win condition. The carbon finance could make the cookstoves distribution programs scalable and enforceable by providing funds. They concluded that cookstoves distribution programs in Peru, Uganda, and Cambodia, the challenge proved the importance of carbon finance to overcome the above mentioned barriers up to certain extent. However, the sustainability and popularity of such programs are yet to be ascertained.

4.3. Health issues

Biomass is burnt inefficiently in open three-stone fires, traditional cookstoves for cooking, and heating applications. Hence, it causes severe health problems in women and children and also affects the environment. Sharma et al. [23] emphasized that the adoption and large-scale propagation of improved stoves could help in improving the health of rural women and in making a more efficient utilization of the available fire-wood resources. This would also stop the large scale deforestration of forest cover in the developing countries, which is responsible for the changes in the climate. Ballard-tremeer and Jawurek [76] compared the thermal efficiencies and the emissions of the five rural cooking devices named an open-fire, an "improved" open fire built on a raised grate, a commercial one-pot metal stove, a prototype two-pot ceramic stove, and a prototype two-pot metal stove by following the standard VITA tests. Their study indicated that the average emission of smoke was lowest for the improved open-fire, while, for the two-pot ceramic stove, it was found to be the highest. Both open-fires emitted the lowest carbon monoxide and sulfur dioxide and the other cookstoves was the higher emitter of carbon monoxide and sulfur dioxide. The average efficiencies of the open-fire, improved open-fire, and the improved cookstoves were found to be 14%, 21%, 20 to 24%, respectively.

Sexton et al. [77] compared the results of an ambient air monitoring study to measure the total suspended particle in Waterbury (Vermont). The measurement of air monitoring was performed during January to early March, 1982 for a wood-burning community. This study was designed to provide data on ambient concentrations of total inhalable and respirable particles in ambient air due to wood-burning. They concluded that major source of airborne particles in residential sections of town was the wood burning. They also concluded that the variation in particulate concentration was significantly observed during the night as compared to the level during afternoon. Raiyani et al. [78] discussed the indoor concentrations of total suspended particulates (TSP), polycyclic aromatic hydrocarbons (PAHs), and the particle size distribution due to biomass fuels in households located in eastern peripheral area of the Ahmadabad agglomeration. They measured the levels of gaseous pollutants, such as, carbon mono-oxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), and Sulfur dioxide (SO_2) across different locations during the cooking hours using different cooking fuels, such as, cattle dung, wood, coal, kerosene or liquid petroleum gas (LPG). The correlation between the pollutants for each type of fuel was presented. They found that the levels of pollutants were relatively high in the houses using biomass as fuel and concluded that the air quality was the worst nearby the users.

Parikh et al. [79] carried out the statistical analysis to examine the correlation between pollution, the type of kitchen, and fuels used for rural houses by first monitoring the indoor air quality (IAQ) followed by regression analysis of 418 households in Tamil Nadu, (India). Exposures to the smoke from the cookstove for females, who were involved in the cooking was also measured with personal monitors. The results showed that the values of respirable particles (PM_{10}) varied from 500 to 2000 g/m^3 depending on the type of kitchen and fuel used. They also concluded that the individuals, who stayed inside the houses during the cooking time, also faced high the concentration of pollutants. Two major findings from this analysis were presented [79], first the improved house designs that paid attention to kitchen location and second, the exposure to pollutants was not limited to the cook only but also to the rest of the family members stay in the house through a “passive cooking effect”.

Wang et al. [80] analyzed the emission characteristics of gaseous pollutants, including volatile organic compounds (VOCs) such as benzene, propylene, acetone, toluene, and acetaldehyde from biomass combustion in the improved cookstoves in rural areas of China using five different type of bio-fuels. From the emission data, they showed that the gaseous pollutants were emitted at higher concentrations in the early stage and lower concentrations in the later stage of combustion. Ryhl-Svendsen et al. [81] conducted the measurements at a Danish Historical Research Center (DHRC) using 17–19th century houses to determine how effective traditional Danish Hearth Systems (DHSs) were in removing smoke from the house, and how much exposure might have existed historically. They measured carbon monoxide (CO) and particulate matter (PM) in two reconstructed Danish farmhouses during 2 weeks of summer. They concluded that a woman, living in such type of houses at that time would have exposed to daily averages of 1.1 ppm of CO and 196 mg/m^3 of PM, which exceeds World Health Organization (WHO) guideline for particulate matter, and was comparable to what was observed in recent times for women in rural areas of the developing countries.

Ding et al. [82] characterized the polycyclic aromatic hydrocarbons (PAHs) present in the indoor air pollution and measured 22 parent PAHs (pPAHs), 12 nitro-PAHs (nPAHs), and 4 oxy-PAHs (oPAHs) in the different locations of a household during summer and winter seasons. These compounds were measured in a typical rural household in Northern China where biomass fuels had been used for heating and cooking purposes. They also investigated the differences and connections between the air pollution in the kitchen, the adjacent bedroom, indoor and outdoor air, winter and summer, and personal exposure to PAHs. They concluded that high PAHs concentrations were measured in the indoor air of the household and the most severe contamination occurred in the kitchen during the winter seasons.

Saud et al. [83] presented the experimentally determined emission factors and estimated the suspended particulate matter (SPM), SO_2, NO, and NO_2 emitted from biomass fuels used as energy in rural areas of Indo-Gangetic Plain (IGP) in India. The average emission factor for SPM from dung cake, fuel-wood, and crop residue over Delhi, Uttar Pradesh, Punjab, Haryana, Uttarakhand, and Bihar were estimated as 16.26–2.29 g kg^{-1}, 4.34–1.06 g kg^{-1} and 7.54–4.17 g kg^{-1}, respectively. Similarly, they also determined the average emission factor for SO_2, NO and NO_2 from dung cake, fuel-wood and crop residue in that region, and the following results are presented as SO_2: 0.28–0.09 g kg^{-1}, 0.26–0.10 g kg^{-1}, and 0.27–0.11 g kg^{-1}; NO: 0.27–0.21 g kg^{-1}, 0.41–0.25 g kg^{-1} and 0.54–0.50 g kg^{-1}; and NO_2: 0.31–0.23 g kg^{-1}, 0.35–0.28 g kg^{-1}, and 0.54–0.47 g kg^{-1}, respectively.

McCracken and Smith [84] studied the thermal efficiency and emissions of an improved biomass cookstove named ‘Plancha mejorada’ with respect to traditional three stone-fire, which was distributed and promoted in Guatemala using water boiling test (WBT) and a standardized cooking test (SCT). There was no significant difference in the efficiency of both the cookstoves. However, the Plancha cookstove took more time to perform both the tests but emit less total suspended particles and carbon mono-oxide (CO) per kJ of useful heat produced. They stated that the relation between improved thermal efficiencies and reduction of indoor pollutants could not be established due to the use of improved biomass cookstoves.

Kandpal et al. [85] studied the indoor air pollution, caused by a traditional and an improved mud cookstove (Sugam-II) by the combustion of four bio-fuels (fuel-wood, dung-cakes, agri-residue, and a mixture of fuel-wood) in it. Their results showed that the concentrations of both carbon mono-oxide (CO) and nitrogen oxide (NO) were higher than prescribed safe limits. The traditional cookstove released 50–40% more formaldehyde (HCHO) than that of the improved mud cookstove [86]. The results indicated that the combustion of cow dung-cakes had considerably higher concentrations of CO in the indoor environment and concentration of air pollutants was found to be the maximum in the kitchen at the height of breathing level of a standing person. Dutta et al. [87] described the change in indoor air quality (IAQ) in the kitchens after the introduction of the ICSs for 1 year under field conditions in Maharashtra (India) after controlling a number of variables. The Appropriate Rural Technology Institute (ARTI), in conjunction with other non-governmental organizations, helped to establish the rural enterprises, which subsequently distributed 30,000 improved cement cookstoves in the state of Maharashtra (India) during Aug., 2004 to Dec., 2005. They reported that CO concentration on an average was reduced within a year of installation of these cookstoves by 39% for the Laxmi and 38% for the Bhagyalaxmi. Similarly, the $PM_{2.5}$ concentration was reduced by 24% for the Laxmi and 49% for the Bhagyalaxmi cookstoves, respectively.

Roden et al. [88] studied the field and laboratory emissions from traditional and improved biomass cookstoves in Honduras. They found that the measured particulate emissions of actual cooking in the field was around three times higher as compared to that of the simulated cooking in the laboratory and the emission factors were highly dependent on the skill of the cook. They measured the emissions from traditional cookstoves, new improved cookstoves, and “broken-in” improved cookstoves for three summers and found that the well-designed improved cookstoves

reduced the PM and CO emission factors significantly as compared to those of the traditional cookstoves. Mestl and Edwards [89] derived more appropriate ventilation factors for the rural population in China based on detailed measurements of indoor air pollution as a part of quantitative assessment of the Chinese National Improved Stove Program (CNISP) in rural China. The fuel-based approach was used to estimate the ventilation factor to account for the differences in the indoor air concentrations and exposures for different parts of the world based on the regional differences in stove technology. They used these revised ventilation factors to estimate the burden of disease from household, who use solid fuels in Shaanxi, Hubei, and Zhejiang provinces of China for cardiopulmonary and cardiovascular diseases.

Armendáriz-Arnez et al. [90] presented the differences in concentrations of particulate matter in indoor air pollution as a result of biomass burning in open-fires cookstove and improved Patsari cookstoves in rural homes of Mexico. They stated that the adverse health impacts could be decreased by instating the improved cookstoves due to the fact that the concentration of particulate matter changed as a result of better combustion in the later stove. Berrueta et al. [91] also presented an integrated energy evaluation of an efficient wood-burning Patsari cookstove in comparison to the traditional cookstoves used in the rural communities of Michoacan (Mexico). The controlled cooking test and kitchen performance test of Patsari stoves showed the fuel-wood savings from 44% to 65% as compared to the traditional open-fires. Granderson et al. [92] examined the fuel-use and design of an improved wood burning Plancha cookstove and compared with the traditional cooking over an open wood-fire. The study was conducted in five households over a period of 4 days using Kitchen Performance Test (KPT) and it was found that the KPT did not indicate any benefit with respect to fuel-use. Although, there are many studies in the literature, which have showed the reduction in the indoor air pollution.

Johnson et al. [93] presented a simple Monte Carlo single-box model, which predicted indoor concentrations by giving a stove's emission performance and usage, as well as kitchen characteristics. They illustrated the utility of the model by presenting a simulated distribution of indoor air pollution concentrations in kitchens based on a series of stove/fuel scenarios and compared them with the air quality guidelines (AQGs) of World Health Organization (WHO) for particulate matter (PM) and carbon mono-oxide (CO). Finally, the model was used to predict the stove performance characteristics that would be required for a given percentage of homes to meet the WHO AQGs. They concluded that there were several potential benefits from their modeling such as: (i) estimation of the potential impacts on indoor air pollution concentrations; (ii) evaluation of the impacts of critical stove performance parameters and environmental variables; and (iii) to provide a means to set stove performance standards, which can be linked with air quality guidelines. Kim et al. [94] reviewed the health risks associated with cooking emissions in relation with the use of biomass and coal fuels. The overall picture of health effects and mechanism associated with each pollutant has been briefly described in Fig. 9 and Table 1.

4.3.1. Respiratory diseases

The fact that air pollution promotes adverse health effects is not new. Studies on pollution derived from indoor sources have received considerably less attention, because its effects are less evident. Saldiva and Miraglia [95] summarized the health consequences of prolonged exposure to indoor air pollution generated by biomass-burning cookstove. This kind of exposure was associated with respiratory, cardiovascular, reproductive, and cancer outcomes. Considering that the use of biomass as fuel for cooking was almost entirely restricted to developing countries. Some projections on the costs due to health consequences of this practice indicated that procedures must be implemented not only to avoid suffering caused to the population but also to remove the extra burden on weak economies. The fire-wood, cow-dung and agro-residues were the type of biomass used for cooking in most of the developing countries.

Levesque et al. [96] conducted a study in the region of Quebec city (Canada) to compare the indoor air quality due to wood usage in heating appliances at homes. They measured the concentration of different contaminants (CO, NO_2, HCHO and PM_{10}) in houses with and without a wood-burning appliances and examined that the respiratory symptoms of the residents in the two categories of homes, as well as the relationship between the measured contaminants and the occurrence of symptoms. The residents, who were exposed to fumes emitted by such an appliance, reported more respiratory illnesses and symptoms. They also concluded

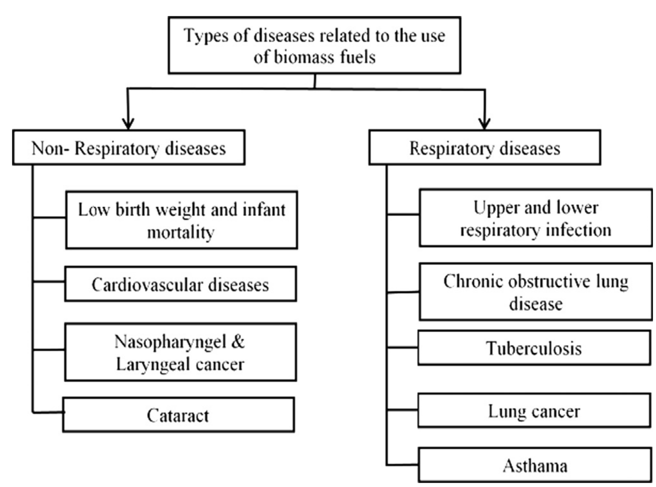


Fig. 9. The impact of biomass fuel smoke on respiratory and other diseases [94].

Table 1
Pollutants and mechanism emitted from biomass fuel [94].

S. No.	Pollutant	Mechanism and health effects
1	Particulate matter	Diseases like asthma, chronic obstructive pulmonary takes place due to the reduced mucociliary clearance; macrophage response and immunity fibrotic reaction.
2	Carbon monoxide	The carbon mono-oxide binds with hemoglobin to produce carboxy-hemoglobin, which reduces oxygen delivery to many organs of human body, causes low birth weight of small children.
3	Polycyclic aromatic hydrocarbons	These are known as carcinogenic compounds causes premature deaths and cancer of lung, mouth, nasopharynx, etc.
4	Nitrogen dioxide	The long term exposure increases the susceptibility to bacterial and viral infections in women and children, which causes respiratory infections.
5	Sulfur dioxide	The serious exposure of sulfur dioxide increases bronchial reactivity, which causes exacerbation of chronic obstructive pulmonary disease and cardiovascular disease.

that the wood burning appeared to be a respiratory health risk for residents if the appliance could not be maintained and used properly.

Verma et al. [97] investigated the effect of different cooking fuels at the concentration of particulate matter (PM) and carbon monoxide (CO) in Gaborone (Botswana). Furthermore, the bad health conditions associated with PM and CO could be associated with different types of fuels used for cooking. The study was conducted by monitoring the indoor air quality in 30 households, representing low, medium and high income groups by conducting interviews on the health conditions of the households involved in cooking. They concluded that more particulate matter was found in the low income group households because they used cow-dung, wood, plastic bags, paraffin, and Chibuku beer cartons as their cooking fuels. They also found that the people of low income households were the most affected as compared to those of the medium and high income groups. Lal et al. [98] carried out a study to characterize and assess the histopathological changes observed in the lungs of rats using different periods of exposure to cow-dung smoke and described the molecular mechanism of cellular toxicity caused by pollutant exposure in lung tissues of rats. They also concluded that the continuous exposure to cow-dung (kanda) smoke may lead to various respiratory disorders and increased the morbidity and mortality in the affected population.

4.3.2. Non-respiratory diseases

Mondal et al. [99] investigated the possibility of genetic damage and repair in a group of premenopausal women in Eastern India, who were chronically exposed to the high level of indoor air pollution (IAP), while, cooking with unprocessed solid biomass such as dung cake, wood, and agricultural wastes. For assessment of genotoxicity, they have used micronucleus (MN) assay in exfoliated buccal (BEC) and airway epithelial cells (AEC) for the assessment of chromosomal damage and single cell gel electrophoresis (Comet assay) in peripheral blood lymphocytes (PBL) for the detection of DNA damage. They concluded that the chronic exposure to biomass smoke causes chromosomal and DNA damage and up-regulation of DNA repair mechanism.

Li et al. [100] evaluated the effectiveness of the improved stoves in two separate programs through air monitoring and biomonitoring in Peru. They measured particulate matter (PM) and carbon mono-oxide (CO) in kitchen and personal air samples of participating households before and after the installation of new stoves with chimney. They concluded that improved stoves with chimney significantly reduced the human exposure to hazardous combustion products including polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM) and CO. However, even after the intervention, urinary hydroxylate PAH (OH-PAH) levels in these subjects were still higher than that of general population in the United States, smokers and at a comparable level to the workers of high occupational exposure to PAHs.

Northcross et al. [101] studied the levels of dioxin exist in village kitchens in Highland Guatemala using biomass fuel for cooking. They stated that the high concentration of smoke from cookstoves inside the kitchen created non-negligible exposures of households to dioxins, though; the fraction of dioxins in wood smoke emissions was very less as compared to the fraction present in other sources. Mondal et al. [102] also investigated the possibility of DNA damage in buccal epithelial cells in a group of premenopausal women from Eastern India, who were chronically exposed to biomass smoke during cooking of food. This cooking was also done for different age groups from the same locality, who were cooking with the cleaner fuel like LPG. In contrast, it was observed that the chronic inhalation of biomass smoke elicits oxidative stress and extensive DNA damage in buccal epithelial cell (BEC) from biomass based cooking fuels.

Very recently, number of authors [103–117] carried out detailed studies about the traditional and improved cookstove using various approaches and presented some new results and strategies for the design, development and dissemination of biomass cookstoves [102–107], while addressing important issues, such as, environment, health and deforestation [108–117]. For example, Tyagi et al. [108] carried out the comparative analysis of four different types of cookstove models using exergetic and energetic approaches. They also discussed the merits and demerits of each cookstove model evaluated experimentally and found that each model has some specific quality over the other models. They also found that the exergy efficiency of all the models is much lesser than that of the energy efficiency, which was due to the fact that the exergy being the quality of energy unlike energy is more significant for all energy conversion devices and recommended that exergy analysis should be taken into consideration for the cookstove design, development and performance evaluation. They also concluded that the results based on the exergy analysis are more appropriate for the analysis, modification, and performance evaluation of biomass cookstove systems and hence, further work is required in this direction. Bentson et al. [109] studied the influence of initial fuel load on fuel to cook for batch loaded charcoal cookstoves, while Singh et al. [110] estimated the missions of PAH from biomass fuels used in rural sector of Indo-Gangetic Plains of India. Gurung and Oh [111] presented as review on the conversion of traditional biomass into modern bioenergy systems to improve the energy situation in Nepal. Khudadad et al. [112] studied the impact of low carbon technologies and products on domestic fuel consumption in Pakistan. Shaughnessy et al. [113] described the detailed study on the small scale electricity generation from a portable biomass cookstove with prototype design and preliminary results. Sesan et al. [114] presented the corporate-led sustainable development strategies for energy poverty alleviation at the bottom of the pyramid in the case of the clean cook for Nigeria. Sperling and Ramaswami [115] explored the health outcomes as a motivator for low-carbon city development narrating the implications for infrastructure interventions in the Asian cities. Jerneck and Olsson [116] presented a smoke-free kitchen by initiating the community based co-production for cleaner cooking and cuts in carbon emissions. Epstein et al. [117] described the detailed impacts of biomass fuels burning in the households, causing the low birth weight and neonatal death in India.

5. Conclusions and recommendations

From the above discussion, it can be concluded that there is a need to replace the traditional and inefficient cooking devices with efficient cooking devices such as the improved and advanced biomass cookstove. From the present study, the following conclusions are drawn:

- The major funding to cookstove dissemination programs is available through carbon revenue, which can help in the development of cookstove market. There are different small scale CDM projects, which have already been started in many countries to reduce the green house gases through the cookstove dissemination programs and hence, can create an example in this regard.
- If the cookstove dissemination programs become successful, they may lead to the sustainable development of the targeted areas and will create the platform for commercialization of cookstove. They can also create job opportunities for young people and local business groups by ensuring the protection of

environment via reduction in deforestation and green house gas emissions.
- There is a need to increase the awareness among the family members regarding the health effects due to biomass fuels that burned into inefficient cooking and heating appliances.

Recommendations

- A cookstove must be carefully designed through testing and performance verification to meet the requirements of good thermal performance and reduction in harmful emissions. There should be internationally defined testing standard and protocols for testing and certification of a cookstove to be disseminated through carbon financing, which can guide the cookstove manufacturers, coordinating and managing entities (CMEs) and other stake holders for maintaining the quality of cookstoves.
- There is a need for contribution of private and public sectors to increase the production and good supply chains of efficient cookstoves all over the world. A mechanism should be developed to reach the end-users of the cookstove. There are different financial sources available for funding in household cookstove business, such as, GEF, IFC, etc. The national policies should be in the favor of cheap and efficient cookstove availability to biomass using families.
- Further, RD&D is required to develop more efficient, clean, durable and affordable cookstove, based on complex heat transfer mechanism involved in the cookstove based on the second law (exergy) analysis, without altering the cooking practices being followed by the end-users.

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